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Study Name: Electra-Optical Imager & Radiometer

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IPO POC: Lt. Kevin Westley

INTERNAL GOVERNMENT STUDIES - FY 1995
Electra-Optical Imager & Radiometer

Presentation/Paper Title	Author(s)	Date
"Final Report, Electro-Optical Imager and Radiometer(EOIR): An NPOESS Internal Concept Study"	J. Alishouse C.R. Rao	SEPT 95
"EO Sensor Design Studies, ICS Final Presentation and Report"	G. Rossano	28 SEPT 95
"EO Sensor Design Studies, ICS Final Presentation"	C.R.Rao	28 SEPT 95
"Calibration of the NPOESS E-O Sensor, ICS Final Presentation"	J. Alishouse	28 SEPT 95
"E-O Sensor Hardware Design Characteristics, Final Report and Future Study Recommendations"	———	SEPT 95
"E-O Band Selection for NPOESS Based on Key Parameters"	D. Lynch	SEPT 95
"EO Imager Baseline Requirements Presentation"	———	JUNE 95
"ICS Interim Status Review Meeting, Electro-Optical Imager & Radiometer"	D. Lynch	29 JUNE 95
"ICS Interim Status Review, EO Imager & Radiometer:	C.R. Rao	29 JUNE 95
"ICS Interim Status Review, Calibration Issues for the NPOESS E-O Sensor"	J. Alishouse	27 JUNE 95
"EO Imager ICS- June Progress Report"	Lt. K. Westley	20 JUNE 95
"EO Imager ICS- May Progress Report"	Lt. K. Westley	16 MAY 95
"EO Imager ICS- April Progress Report"	Lt. K. Westley	2 MAY 95
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DRAFT

Electro-Optical Imager and Radiometer (EOIR): An NPOESS Internal Concept Study

Final Report
Submitted by

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To

National Polar-orbiting Operational Environmental Satellite System
Integrated Program Office

September 1995

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Prefatory Note

This is a brief report on the work performed over the period May-September 1995 under the Internal Concept Study of the Electro-Optical Imager and Radiometer, sponsored by the Integrated Program Office, National Polar-orbitingoperational Environmental Satellite System. We have drawn freely from research conducted at the NOAA/NESDIS'-Office of Research and Applications, material in the open literature, unrefereed scientific and technical reports, unpublished agency documents, and trade publications of private industry. It is thus likely that some of the technical information may be revised in future. Also, in view of the limited circulation of this document, we have not yet obtained clearances from the various publishers for inclusion of material, mainly illustrations, from their publications. Mention of any trade or brand names should not be construed as an endorsement of the product or the procedure by the U.S. Government.

C.R.Nagaraja Rao

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Electra-Optical Imager and Radiometer (EOIR): An NPOESS Internal Concept Study

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Abstract

This report summarizes our activities over the 4-month period from May 1995 to September 1995 under an internal concept study of an Electra-Optical Imager and Radiometer(EOIR) conducted for the Integrated Program Office, National Polar-orbiting Operational Environmental Satellite System(NPOESS). The activities were centered on the development of a high level concept of an Electro-Optical Imager and Radiometer for NPOESS that would meet both the imaging and radiometric needs of the civilian and defence communities in an optimum manner. Toward this end, we have completed a survey of the design features of the various currently operational and proposed sensors for use on NOAA's polar orbiters, and on the EOS platform directed towards the generation of environmental products similar to those expected from the EOIR. The instruments studied included the Advanced Very High Resolution Radiometer (AVHRR), the Operational Multispectral Imaging Suite(OMIS), the Moderate Resolution Imaging Spectrometer (MODIS), the Multi-Angle Imaging SpectroRadiometer (MISR), Sea-viewing Wide Field-of-View Sensor (SeaWiFS), the Along-Track Scanning Radiometer (ATSR), and Clouds and the Earth's Radiant Energy System (CERES). Based on the results of this survey, and on the preliminary requirement specifications for some of the key and non-key parameters listed in the draft of the Integrated Operational Requirements Document(December 1994), and which, in our opinion, can be derived from measurements of the upwelling radiance in the visible and infrared regions of the spectrum($\approx$0.4 - 16μm), we suggest that the <u>basic</u> instrument be designed to measure the radiation in spectral intervals around 0.64, 0.87, 1.6, 3.7, 8.6, 10.8, and 12μm; an additional broad-band channel from -0.4 to 1μm should also be included for low light level imagery. The underlying premise is that the basic instrument should have the capabilities associated with the Advanced Very High Resolution Radiometer, and its intended successor, the Visible, Infrared Scanning Radiometer and the Operational Multispectral Imaging Suite. Since the spectral region from $\approx$0.4 to 16μm encompasses the visible and near-infrared spectral intervals that are normally used to sense ocean colour, the impact of including the same in the EOIR on cost, configuration, optical design, size, power consumption, and adaptability of the instrument to different spacecraft should be investigated. It is also recommended that the instrument should, in the minimum, have an on board calibration device using the sun as

the calibration source. The options of on board calibration devices made up of stable light sources, and multiple black bodies should also be explored. Preliminary studies along these lines have been completed.

As part of the internal concept study, a reference radiation data base has been established in the visible and near-infrared regions (≈ 0.4 - $2 \mu m$) of the spectrum for use in future radiometric simulations of the performance of the EOIR. Basic features and use of the radiation data base are illustrated. The concept of a Value-Added Environmental Data Record (VAEDR) to enhance the products generated with the EOIR by the fusion of similar products from other instruments is briefly discussed.

1. Introduction

This document is a brief summary of the activities performed to date as part of the Internal Concept Study of the Electro-Optical Imager and Radiometer(EOIR) at the NOAA/NESDIS Office of. Research and Applications. The EOIR is intended to serve the imaging an-d radiometric needs of the civilian and defense communities in the visible and infrared regions of spectrum, combining in an optimum manner the capabilities of NOAA's Advanced Very High Resolution Radiometer(AVHRR) and the Visible, Infrared Scanning Radiometer(VIRSR)--the AVHRR's intended successor-- and DoD's Operational Multispectral Imaging Suite(OMIS). The possibility of incorporating the capabilities of dedicated ocean sensors such as the Sea-viewing Wide Field-of-View Sensor(SeaWiFS) would also be explored. It was decided at the outset that heritage would play an important role in our study, so that we would appropriately draw upon the experience gained with the past and current operational meteorological sensors, and gain from the lessons learnt in the course of the design of sensors that have been built for the immediate future. Toward this end, during the initial phase of activity over the 4-month period May-September 1995, a survey of current and proposed sensors for the Earth system, which'either drew upon the AVHRR, or which could contribute to the design of the Electra-Optical Imager and Radiometer was completed to delineate the following: (a) basic physics underlying the choice of the spectral intervals for measurements; (b) the method adopted to translate product requirements into sensor requirements; (c) choice of detectors and characterization of detector performance; (d) pre-launch calibration(spectral and radiometric) ; (e) post-launch calibration, using either on board calibrators, or vicarious techniques. The instruments reviewed were: (1) the Advanced Very High Resolution Radiometer(versions 2 and 3); (2) the Visible, Infrared Scanning Radiometer(VIRSR; performance specifications); (3) Operartional Multispectral Imaging Suite(limited information available in.the public domain); (4) the Moderate Resolution Imaging Radiometer(MODIS); (5) the Multi-angle Imaging Spectro-Radiometer(MISR); (6) the Sea-viewing Wide Field-of-View Sensor(SeaWiFS); (7) the Along Track Scanning Radiometer; and (7) Clouds and Earth's Radiant Energy System(CERES) .

We have also examined the notion of a "Value-Added Environmental Data Record(VAEDR) ." This would essentially imply the augmentation or enhancement of a product derived from the EOIR with the same product derived from a similar sensor on a different platform, or from a different sensor altogether. An example would be the fusion of sea surface temperature(SST) records from the EOIR and the ATSR or its successors; or the fusion of the aerosol product from the EOIR, MODIS, MISR, SeaWiFS, and sensors like the Stratospheric Aerosol Gas Experiment(SAGE) and Polarization and Directionality of Earth Reflectances(POLDER). The attendant issues of cross-sensor calibration; the impact of differences in spatial and temporal resolutions; and of differences in product algorithms are being studied. It should be emphasized that, the concept of VAEDR is solely directed towards augmenting the products derived from the EOIR.

Also, in the true spirit of convergence of the remote sensing needs of the civilian and defence communities, we have used the terms "geophysical product", "environmental product", "product" and "Environmental Data Record" interchangeably in what follows.

2. Basic design philosophy

Our concept of the evolution of the Electra-Optical Imager and Radiometer is shown in Fig.1. A product is generated from the calibrated radiances measured by the EOIR with the use of an algorithm. The algorithm may require the use of radiances measured in more than one spectral interval, and may also require the fusion of data from other sources. We shall refer to them as the input parameters. Each of these parameters would in turn be required to meet certain accuracy/precision/stability criteria in **order** to meet the product requirements. Thus, the input parameter requirements will define the sensor performance requirements, and hence, the sensor specifications. These have to be mapped on to the current technology capabilities and constraints, and on to the constraints imposed by cost and schedule. This would invariably result in revisions of sensor specifications whose impact on the product requirements should in turn be evaluated. Thus, we are looking at an iterative procedure to render optimum the EOIR performance and products. The final design would evolve through iterative end-to-end model simulations of the EOIR for which we would use as initial conditions our understanding of the present capabilities of sensors like the AVHRR, and also the interrelationships that exist among the products. Attention will also be paid to the algorithm-specific factors which impact on the design of the sensor.

The retrieval of sea surface temperature (SST) from the infrared radiances measured in the atmospheric window regions (-3.7, 10.8, and 12 μm) by the AVHRR is a good illustration'of this design philosophy. Our experience to date clearly shows that the relationship between the noise equivalent temperature associated with the detector, and attainable accuracies of SST retrieval is infulenced by the SST retrieval algorithm used. In addition, in order to attain accuracies of a few tenths of a degree C in the retrieved SSTs, appropriate corrections must be made for the radiative effects of atmospheric aerosols, especially after volcanic eruptions, thereby leading to a link between the SST and aerosol products. The correction procedures require a knowledge of the columnar abundance of atmospheric aerosols, their vertical distribution, and their optical and radiative properties. The columnar abundance of atmospheric aerosols is generally determined from the upwelling radiances in the visible and near-infrared regions of the spectrum; it is thus conceivable that attainable accuracies in the determination of the columnar abundance of

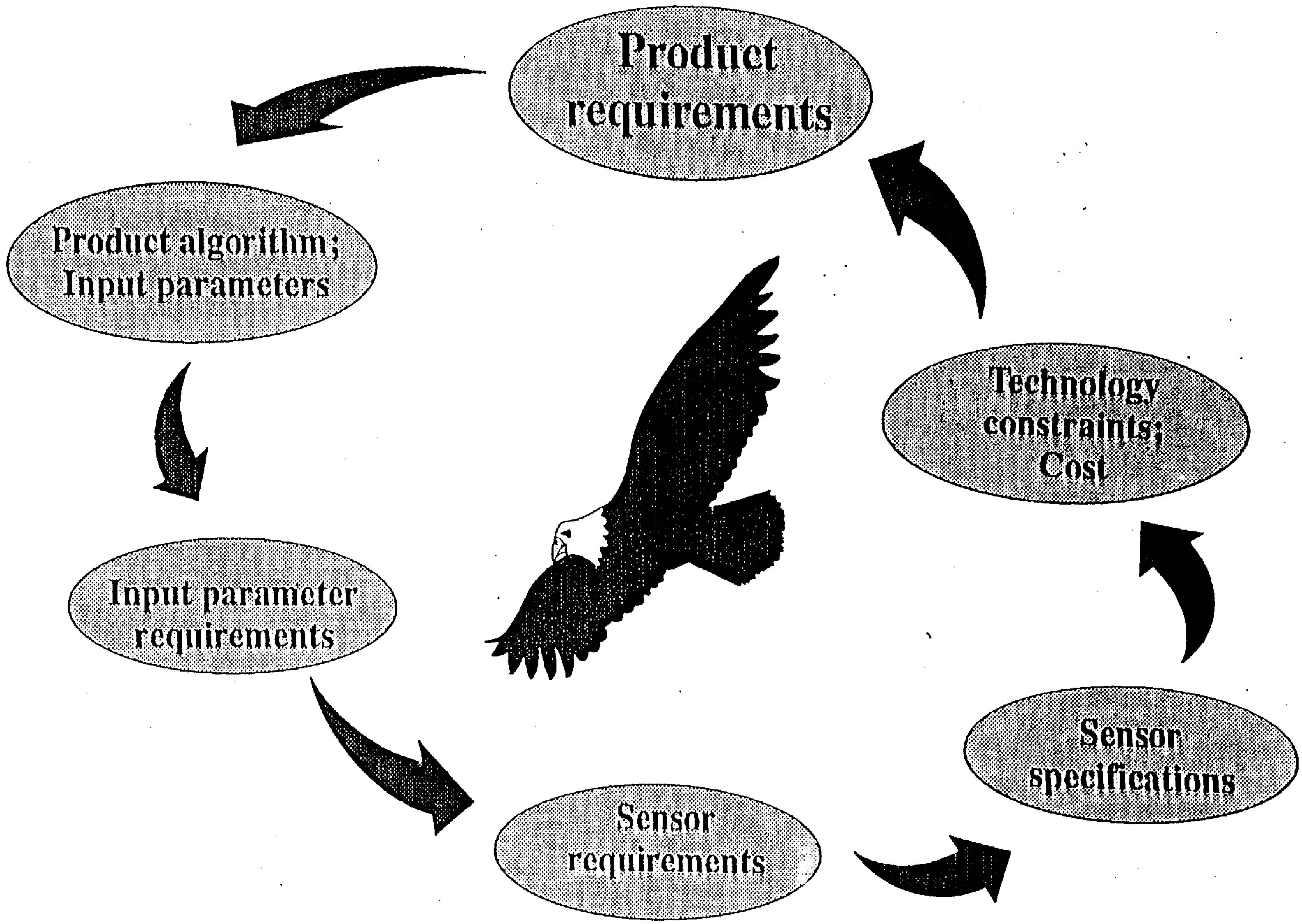

Figure 1: Evolution of a Sensor

aerosols and related optical and radiative properties may play an important role in the attainable accuracy'for the SST product, and thus on the specification not only for the visible and near-infrared channels of the EOIR.but also for the thermal infrared channels. Similarly, the attainable accuracies in the vegetation index product may be defined by the accuracy with which the measurements can be made in the visible and near-infrared regions and by the accuracy with which the aerosol product is determined as it figures prominently in the atmospheric correction algorithms. This interrelationship between products will be one of the important factors that will govern the EOIR specifications, and also the realizability of a product with very stringent requirements for accuracy. Greater details of this inter-relationship between products, and its impact on the design of the EOIR will be given in the product dossiers in preparation.

3. Spectral signatures of the atmosphere and surface

Central to the remote sensing of the Earth's atmosphere and surface is the identification of the spectral signatures associated with them 'and, the development of the ability to isolate, to the extent practicable, the similar effects that the atmosphere and surface, may have on the upwelling radiance at the top of the atmosphere. The spectral signatures are the **physical** manifestations of the dispersive(wavelength dependent) processes of absorption, scattering, emission, and reflection of radiation by the gaseous and particulate constituents of the atmosphere, and by the surface. Thus, it is to be expected that multi-spectral, multi-angle measurements of the upwelling radiance would contain information on the atmosphere and surface. A judicious choice of spectral intervals would help in the separation, to a high degree, of the atmosphere and surface effects. Measurements of the polarization of the upwelling radiance in quasi-monochromatic spectral intervals(Radiance or specific intensity; type of polarization--linear, circular, or elliptical; degree of polarization; and orientation of the plane of polarization) have potential to add to the information we can derive 'about the atmosphere and surface. This is the basis for the Polarization and Directionality of Earth Reflectances(POLDER) scheduled for flight on the Advanced Earth Observing Satellite(ADEOS) and the Earth Observing Scanning Polarimeter(EOSP) scheduled for flight on the Earth Observing System(EOS) AM-2 and AM-3 platforms.

We have shown in Fig.2 typical atmospheric absorption spectra in the spectral region of interest to us, and in Figs. 3, and 4 representative reflection spectra for various types of surfaces. It is apparent from the atmospheric absorption spectra(under cloud free conditions) that the atmosphere is fairly transparent in the visible, falling within the short-wave or solar radiation regime(wavelengths less than $\approx 5\mu m$), and in the spectral intervals centered around 1.6, 2.2, and $3.7\mu m$; and in the atmospheric window region from -8 to $13\mu m$ lying in the long-wave

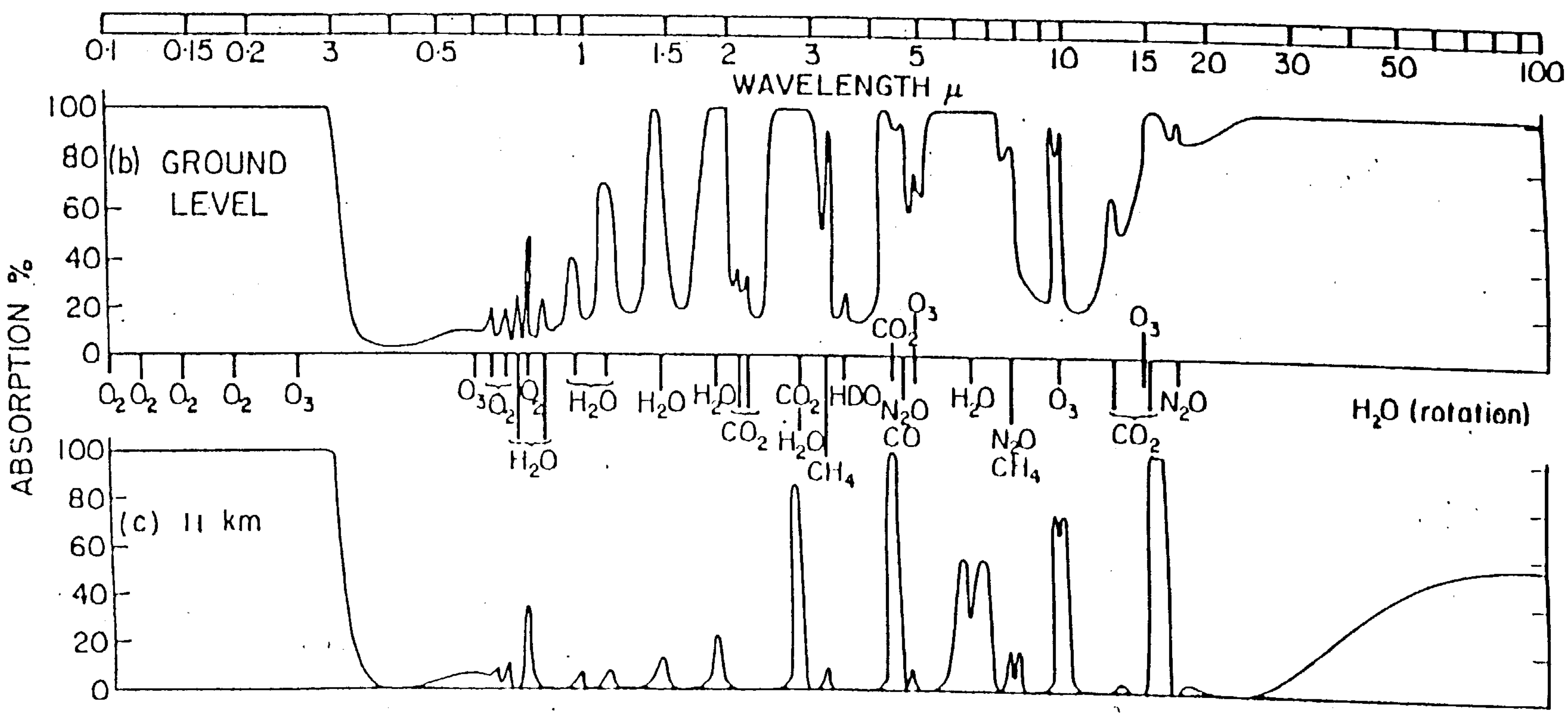

Figure 2. Atmospheric absorption spectra; the differences between the spectrum at ground level, and at an altitude of 11km are due to the vertical distribution of the various gaseous atmospheric constituents.

(From Atmospheric Radiation , R.M.Goody, The Clarendon Press, Oxford, 1964)

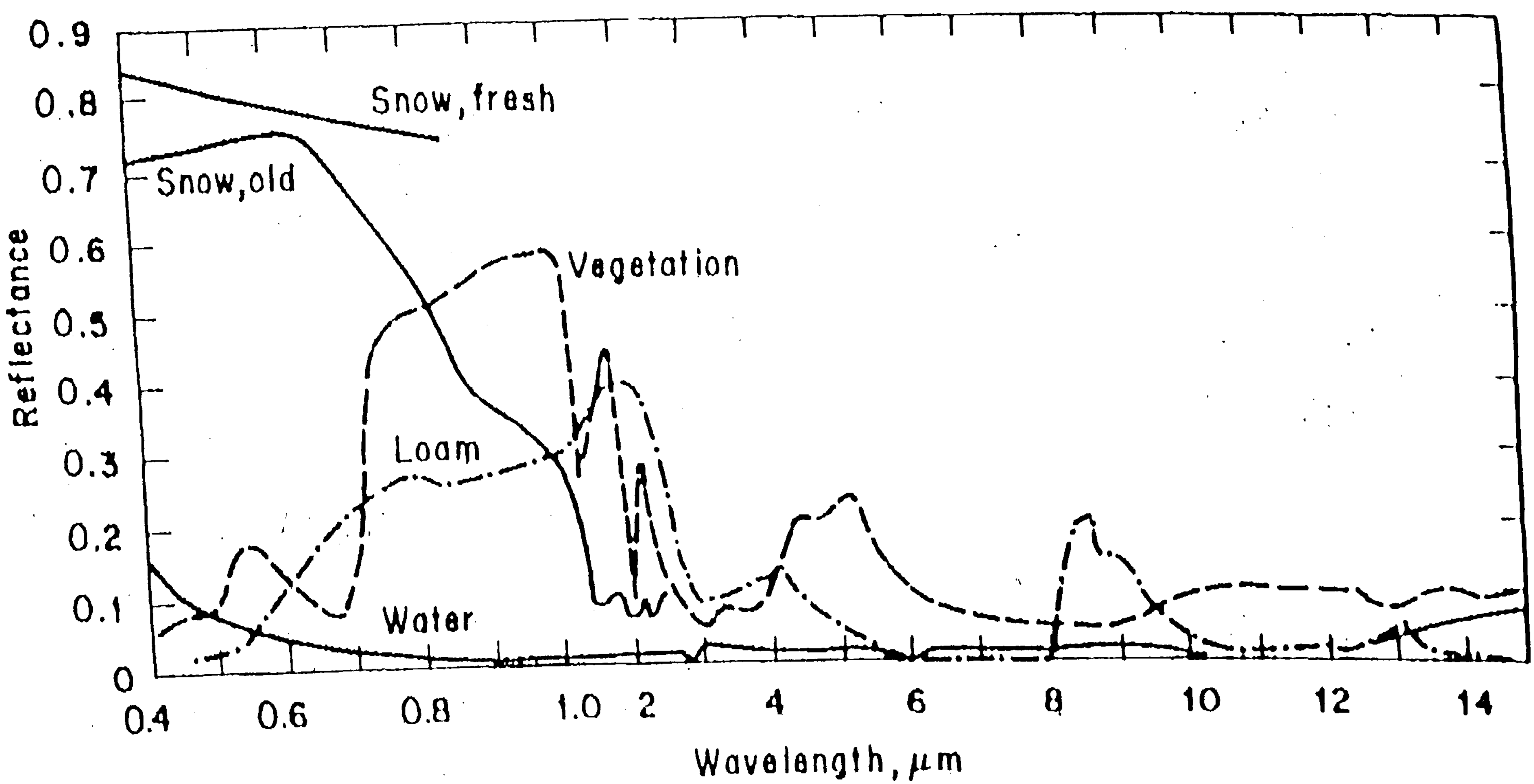

Figure 3: Typical Reflectance of Water Surface, Snow, Dry Soil, and Vegetation

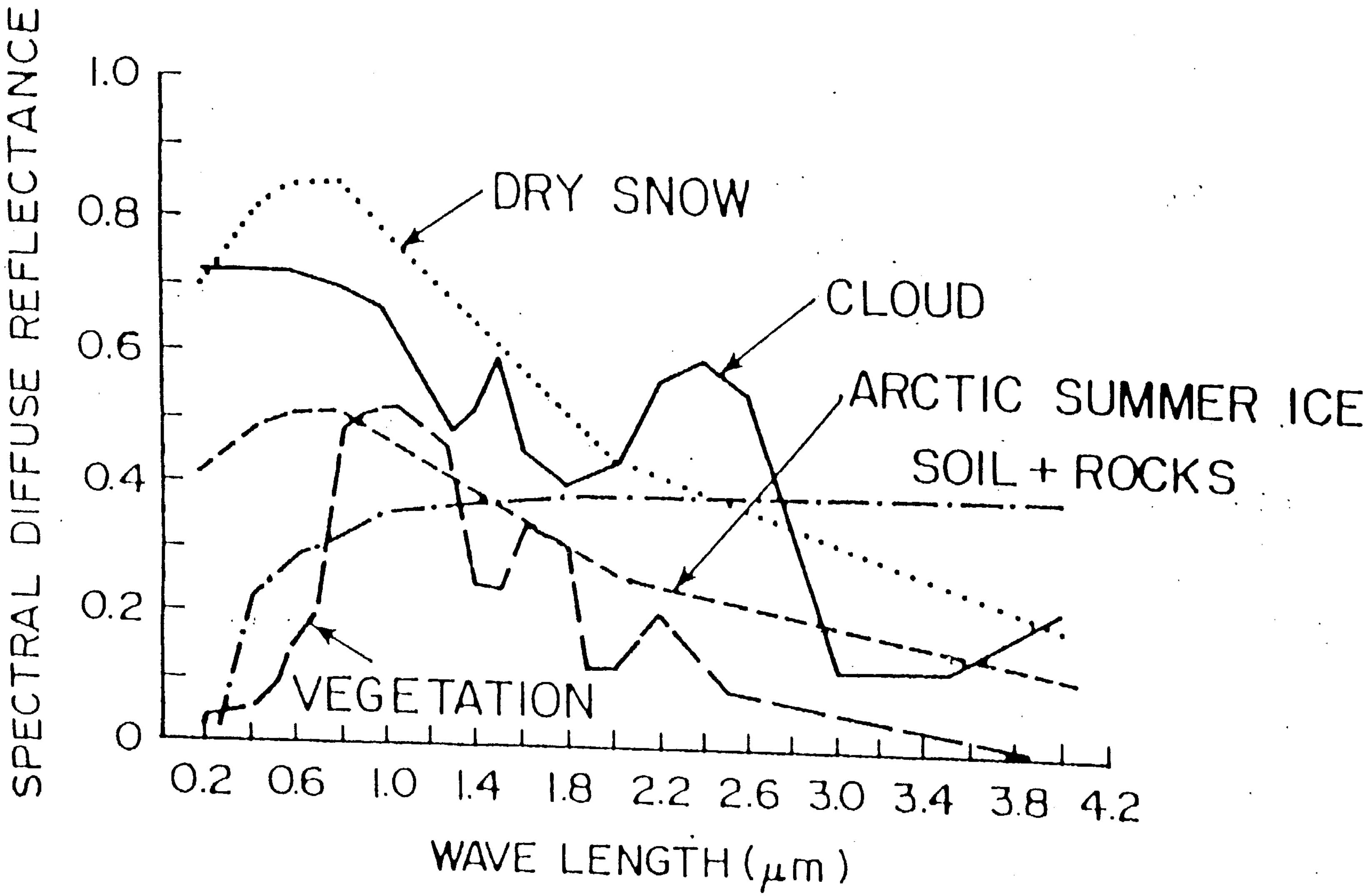

Figure 4: Typical Spectral Diffuse Reflectance of Snow, Ice, Soil, and Vegetation

radiation regime (wavelengths greater than ≈5μm). It should be noted that the vertical distribution of the atmospheric constituents will define the absorption spectrum at different levels in the atmosphere as seen in Fig.2. Thus, detection of atmospheric species is facilitated by making measurements in the region of the spectrum where they exhibit a strong absorption (and emission) signature, and characterization of'the surface is facilitated in the region of the spectrum where atmospheric transparency is high. It should be noted that the reflection spectra shown in Figs.3 and 4 are only representative, and some of the information is dated. Reflection measurements have been made with instruments of different degrees of sophistication measuring the ratio of either the reflected radiance or irradiance to the incident radiance or irradiance. The differences in the techniques employed to measure the reflected radiation, and the myriad of conventions presently in use to describe the process of reflection of radiation render the comparative evaluation of the reflectance spectra rather difficult. It is our intention to recast the available spectral reflection data into a common format, to the extent practicable, if the internal concept studied is continued in FY1996. It is therefore suggested that the data shown should be used as an indicator of the potential information content of the reflectance spectra, and not as an absolute measure of the same.

By virtue of their absorption, emission, and scattering of radiation, both aerosols and clouds affect the upwelling radiance at the top of the atmosphere. This is the basis for various techniques that are presently in use, or have been proposed, for remote retrieval of the columnar abundance, and microphysical properties of aerosols and for the characaterization of clouds. In addition, colorimetric description of the atmosphere and its contrast transmission properties are also governed by the scattering and absorption processes occurring in the visible region of the spectrum, and by reflection at the surface.

Spectral information of the type shown in Figs.2,3, and 4 is the basis for the choice of spectral channels of the currently operational and proposed meteorological satellite operational and research sensors. We have shown in Table 1 the spectral intervals in which some of the atmospheric and surface constituents show their signature, or which have been used, or proposed, for the retrieval of the same; and in Table 2 the basic attributes of the various sensors 'we referred to earlier, namely, the overall spectral region they cover in their various channels, the number of spectral channels, and the Earth system products they are intended to measure; the product list is only representative, and we have included operational, experimental, and proposed products. It is apparent from this table why we felt the compelling need to draw upon heritage in our internal concept study of the EOIR.

More detailed tables like this will be prepared to help in the design of the EOIR. Information shown in Table lb also points

Table 1. Representative. atmospheric and surface spectral signatures .

Atmospheric/ Surface Parameter	Spectral Interval
Sea surface temperature	Atmospheric Window $\approx$3-4μm; 10-13μm
Vegetation	Visible and near-infrared $\approx$0.55, 0.64, 0.87μm
Snow/cloud differences	Near-infrared $\approx$1.6μm
Aerosols	Visible and near infrared ($\approx$0.5 - 2μm)
Ocean color	Visible and near-infrared ($\approx$0.4-0.9μm)
Clouds/Surface Temperature	Infrared $\approx$4μm
Clouds	Infrared $\approx$11-14μm
Forest fires	Infrared $\approx$3.7μm

Table 2. Operational and Research Environmental Sensors and Products

Sensor	Spectral Region and Number of Channels	Representative Products
AVHRR	≈0.5 to 13μm 4 channels(#1) 5 channels(#2) 6 channels(#3)	Sea surface temperature; Vegetation Index; short- and long-wave radiation components; Clouds; Insolation: Atmospheric aerosols; Snow cover
MODIS	≈0.6 to 15μm 36 channels	Vegetative chlorophyll absorption; Land cover boundaries; Leaf canopy properties; Snow/Cloud differences; Ocean colour; Submarine and atmospheric aerosols; Clouds; Surface temperature; Sea surface temperature
MISR	≈0.4 to 0.9μm 4 channels	Cloud bidirectional reflectance distribution function; Aerosols; Top-of-the atmosphere hemispherical albedo; Surface bidirectional distribution function; vegetation index; photosynthetic capacity; Phytoplankton pigment concentration
SeaWiFS	≈0.4 to 0.9μm 8 channels	Ocean's role n global carbon cycle; Primary marine phytoplankton production; production; Dynamics of ocean and coastal currents; aerosols
ATSR	-1.5 to 13μm 4 channels; 24 and 36 GHz	Sea surface temperature; Total water vapour content; Microwave brightness temperature; cloud detection
VIRSR (Design)	≈0.5 to 13μm 7 channels	See listing for AVHRR
OMIS (Design)	≈0.4 to 13μm 7 channels plus low light level channel: ≈0.4 to 1.0μm	Imagery?

possibility that exists for the generation of the Value-Added Environmental Data Record (VAEDR). While the EOIR functions as the primary visible and infrared radiometer and imager for the NPOESS, combining the proposed functions of the VIRSR and OMIS in a **synergistic** manner, it will be-worthwhile examining to whatextent the products generated from the EOIR could be enhanced by ingesting data from other sources. We shall come back to this point later.

4. Detectors

The EOIR is required to cover the spectral range from $\approx 0.4\mu m$ to $15\mu m$ to be able to generate the variety of atmospheric, land, and ocean products nominally associated with the VIRSR and OMIS. The detectors generally used to cover this broad spectral region are: Silicon-based detectors for the visible and near-infrared regions; Indium-Antimonide and Indium-Gallium-Arsenide detectors for the middle infrared (up to $\approx 5\mu m$), and Mercury-Cadmium-Telluride detectors for the thermal infrared region which encompasses the atmospheric window. Some of the characteristics of this family of detectors are shown in Table 3., and we have shown in Figs.5,6,7,8,9 and 10 the wavelength dependent sensitivity of response of various solid state detectors normally used in satellite instruments over the spectral region of interest.

The Mercury-Cadmium-Telluride detectors used in the photoconductive mode in the thermal infrared region of the spectrum are observed to exhibit nonlinear response. Such nonlinearities have been noticed in the response of channels 4 (≈ 10.3-$11.3\mu m$) and 5 (≈ 11.5-$12.5\mu m$) of the AVHRRs over the entire range of Earth-scene temperatures. This is seen in Fig.11 where we have shown the residuals from a linear fit for laboratory calibration as a function of scene radiance/temperature. This behaviour necessitates the development of nonlinearity corrections to ensure the accuracy of scene brightness temperatures measured in channels 4 (≈ 10.3 - $11.3\mu m$) and 5 (≈ 11.5 - $12.5\mu m$). It has been suggested that the nonlinearities may be negligible if the

Table 3 : Comparison of Solid State Detector Material

Detector	Si	InSb	InGaAs	HgCdTe
Operating Temperature (°K)	77 to 300	77	77 to 300	77 - 80
Wavelength Range (μm)	0.5 to 1.1	1.0 to 5.5	1.0 to 2.6	1 to 30
Sensitivity (Jones+)	10^{12} to 10^{13}	10^{11}	10^{11} to 10^{12}	10^{9} to 10^{11}
Response Time (μsec)	.05 - 5	< 1	< 1	1 to 2
Operating Mode	pv or pc	pv	pv	pv or pc
Notes				

+ 1 Jones = 1 cm $Hz^{1/2}$ W-1

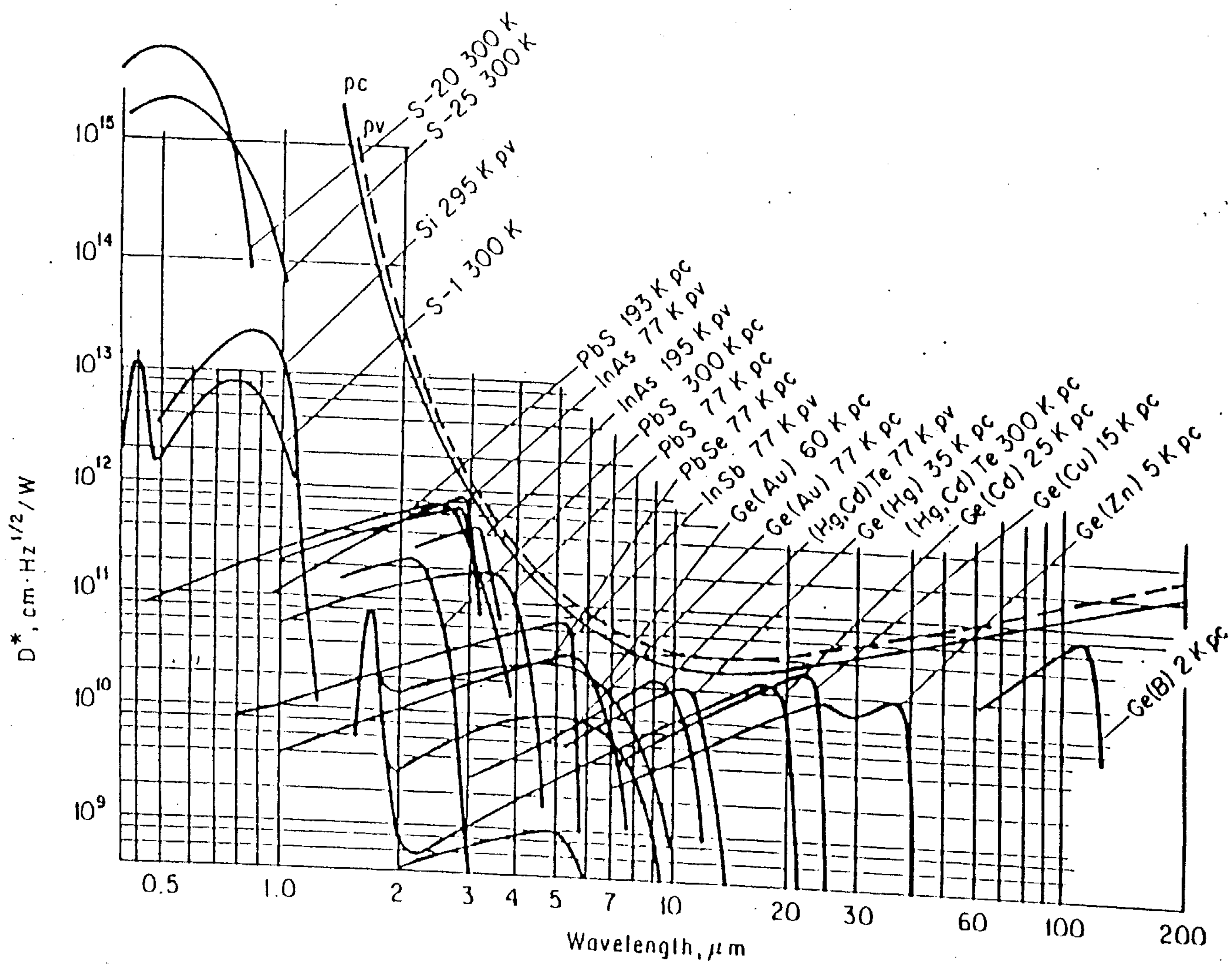

Figure 5: D* vs. λ for selected detectors

(From Handbook of Optics, M.Bass(Editor), McGraw-Hill, Inc., New York)

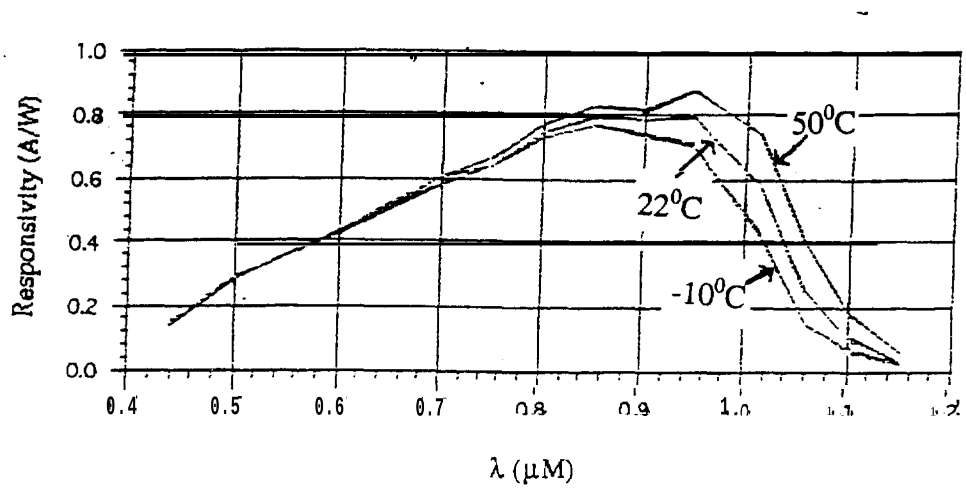

Figure 6. Responsivity of typical silicon photodiodes

(From AVHRR/2: ~~Advanced Verv~~ High-Resolution-Radiometer. Technical Description , ITT Aerospace/Communications, Fort Wayne, Indiana, 1982)

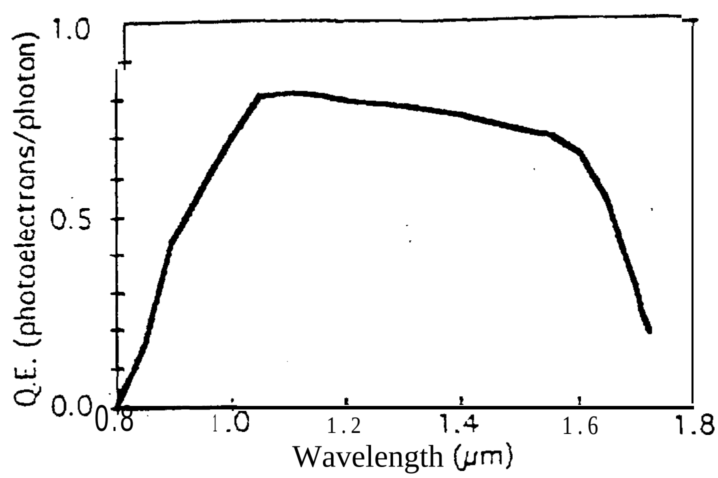

Figure 7 Spectral dependence of quantum efficiency for an InGaAs detector having a cutoff of 1.67 µm. *(Sensors Unlimited, data sheet.)*

(From Handbook of Optics , M.Bass(Editor), McGraw-Hill, Inc., New York)

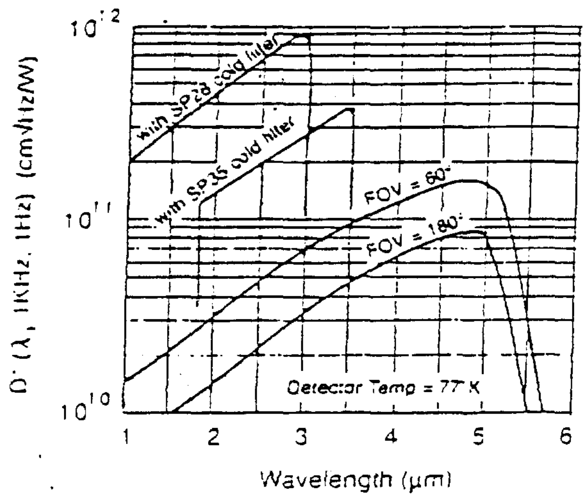

Figure 8 D^* as a function of wavelength for an InSb detector operating at 77 K. *(EG&G Judson, Infrared Detectors, 1994.)*

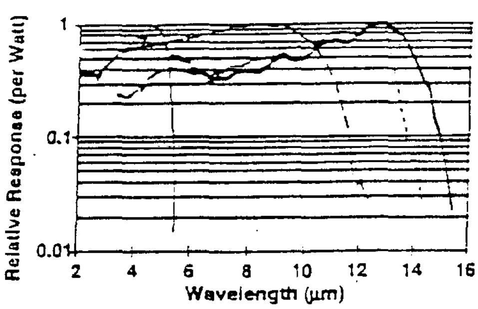

Figure 9 Relative spectral response per watt at 80 K for photoconductive HgCdTe detectors with antireflection coating. The curves are normalized to unity at peak value. The spectral cutoff can be adjusted by varying the ratio of HgTe to CdTe in the alloy.

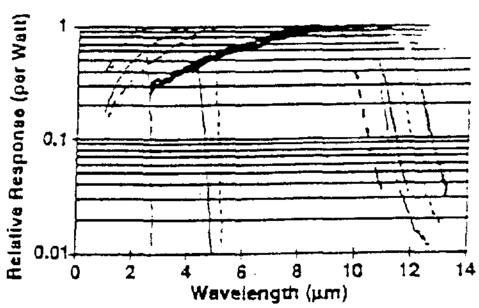

Figure 10 Relative spectral response per watt at 80 K for photovoltaic HgCdTe detectors without antireflection coating. The curves are normalized to unity at peak value. The spectral cutoff can be adjusted by varying the ratio of HgTe to CdTe in the alloy.

(From <u>Handbook of Optics</u>, M.Bass(Editor), McGraw-Hill, Inc., New York)

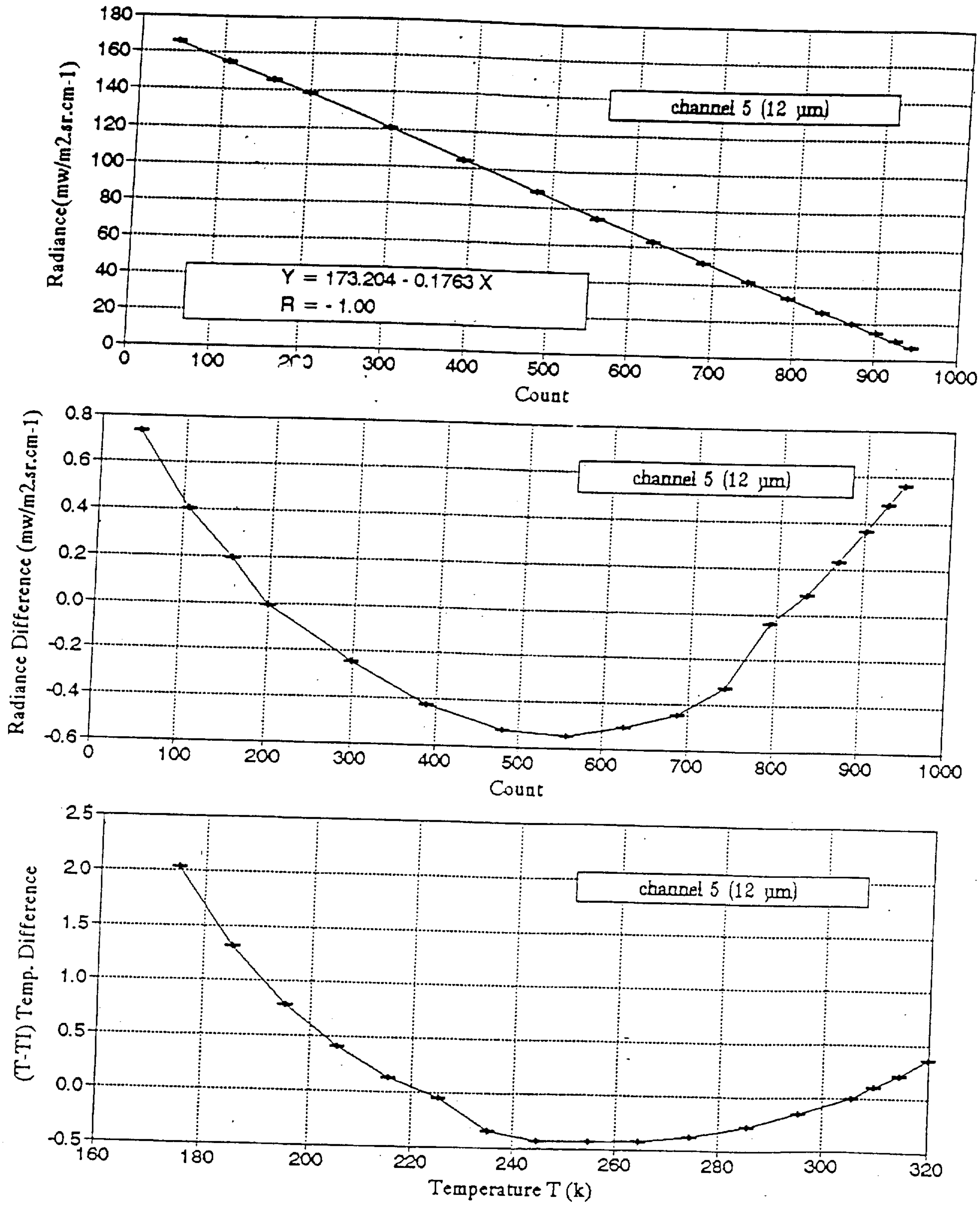

Figure 11: Nonlinear response of the Mercury-Cadmium-Telluride detector

Mercury-Cadmium-Telluride detectors are used in the photo-voltaic mode. While it is the accepted notion that operation in the photovoltaic mode results in stronger approximation towards linear response compared to operation in the photoconductive mode, experimental data to determine the magnitude of the nonlinearity is not readily available. The performance of the Indium-Gallium-Arsenide detectors used in the spectral region around 1.6μm should also be evaluated.

5. Visible and near infrared radiative transfer simulations

As the first stage in the end-to-end model simulations of the EOIR which we mentioned earlier, we have made over **60,000** computations of the upwelling radiance at the wavelengths of 0.633, 0.842, and 1.6μm in a cloud-free model of the tropical atmosphere for different combinations of surface Lambertian albedo and atmospheric turbidity, using the normal attenuation aerosol optical thickness at 0.5μm to label the state of atmospheric turbidity. We have used desert aerosols in the model simulations performed with the LOWTRAN-7 radiative transfer code. It should be noted that the three wavelengths we have chosen are representative of channels 1,2, and 3A of version 3 of the AVHRR scheduled for flight on the NOAA K,L, and M spacecraft. Typical results are shown in Figs.6, 7, and 8., here θ_0, θ, and ϕ are respectively the solar zenith, the satellite zenith, and relative azimuth angles.

It is seen from the data shown in Figs.12, 13, and 14 that the upwelling radiance at the top of the atmosphere at the wavelength of 1.6μm is about an order of magnitude smaller than the upwelling radiance at the wavelength of 0.633μm where as the upwelling radiances at 0.633μm and 0.842μm are comparable. The data also bring out the competing and compensating roles of the atmospheric aerosols and the Lambertian surface. When the surface albedo is low, the upwelling radiance increases with increasing atmospheric turbidity(or, equivalently, increasing columnar aerosol burden) labelled in terms of the aerosol optical thickness at 0.5μm. As the surface albedo increases, the rate of increase of the upwelling radiance with atmospheric turbidity decreases. When the enhancement of the upwelling radiation at the top of the atmosphere due to increases in atmospheric turbidity is offset by the decrease in the surface-reflected contribution to the upwelling radiation because of the attenuation of the surface-reflected radiation by the overlying atmospheric aerosols, the upwelling radiation becomes independent of the columnar aerosol. This occurs for different combinations of atmospheric turbidity, surface albedo, and illumination and observation geometry. Beyond this critical albedo, increases in atmospheric turbidity result in decreases in the upwelling radiation. Different aerosol radiative and optical properties, differences in the solar zenith, satellite zenith, and relative azimuth angles, and departure of the surface reflection properties from those of a Lambertian surface used in the present radiative transfer model, while affecting the critical combination of surface albedo and atmospheric turbidity, will still bring out the competing and compensating effects of these two radiative transfer input parameters.

Some of the immediate applications of these radiance computations are: (a) Determination of the dynamic range of the EOIR in these spectral regions; (2) Delineation of atmospheric and surface effects that should be considered in any EDR-based sensor specification; (3) Development of insight(in the first approximation) into atmospheric correction algorithms that would impact several EOIR products; and (4) Generation of a reference radiance data base that can be utilized to determine the information content of multi-spectral measurements by instruments like the EOIR. Subject to the continuance of this internal concept study, and availability of appropriate resources, this study will be extended to different surface characterizations(other than Lambertian), and the resulting data base so formatted and archived that it will be easily accessible to the user community.

6. Calibration

6.1 General

Pre- and post-launch calibration of the various satellite instruments making up the NPOESS suite should be given the highest priority in order to ensure the integrity, utility, and long-term continuity of the environmental data records that would be generated. While pre-launch calibration would ensure compliance to specifications as determined by the IORD requirements, and in the event of non-compliance, would provide insight into instrument problems and remedial measures, post-launch calibration will provide the means for characterizing the performance of the instrument in the dynamical orbital environment which is crucial to the establishment of the viability and utility of the environmental data records that would be generated. Post-launch calibration can be achieved in an optimum manner with on board calibrators. Thus on board calibrators should be an integral part of the various instruments that would constitute the NPOESS suite-- especially of those intended to generate a number of key and non-key NPOESS parameters such as the Electro-Optical Imager and Radiometer. Also, proper EOIR calibration will be vital to the generation of Value-Added Environmental Data Records(VAEDR) mentioned earlier. Finally, since the acceptance and use of a satellite-derived environmental product is determined by how good it is, and by the confidence it engenders amongst the user community, proper instrument calibration will have great impact on programmatic decisions.

The Calibration/Validation working group of the Committee on Earth Observation Satellites(CEOS) defines calibration as "the process of quantitatively defining the system response to known controlled signal inputs." We shall expand this definition to include characterization of the instrument in terms of its spectral

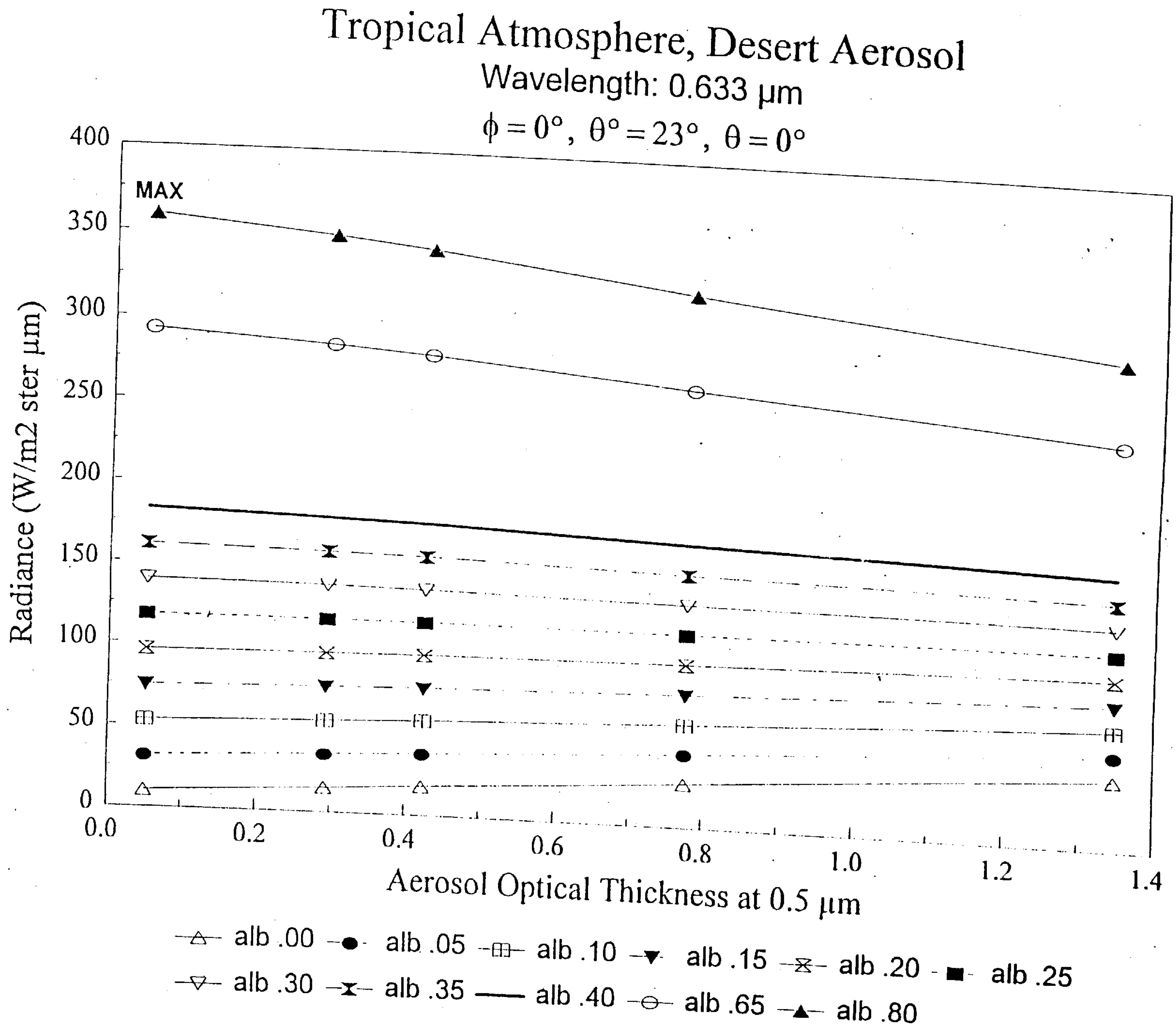

Figure 12 : Upwelling radiation at the top of the atmosphere

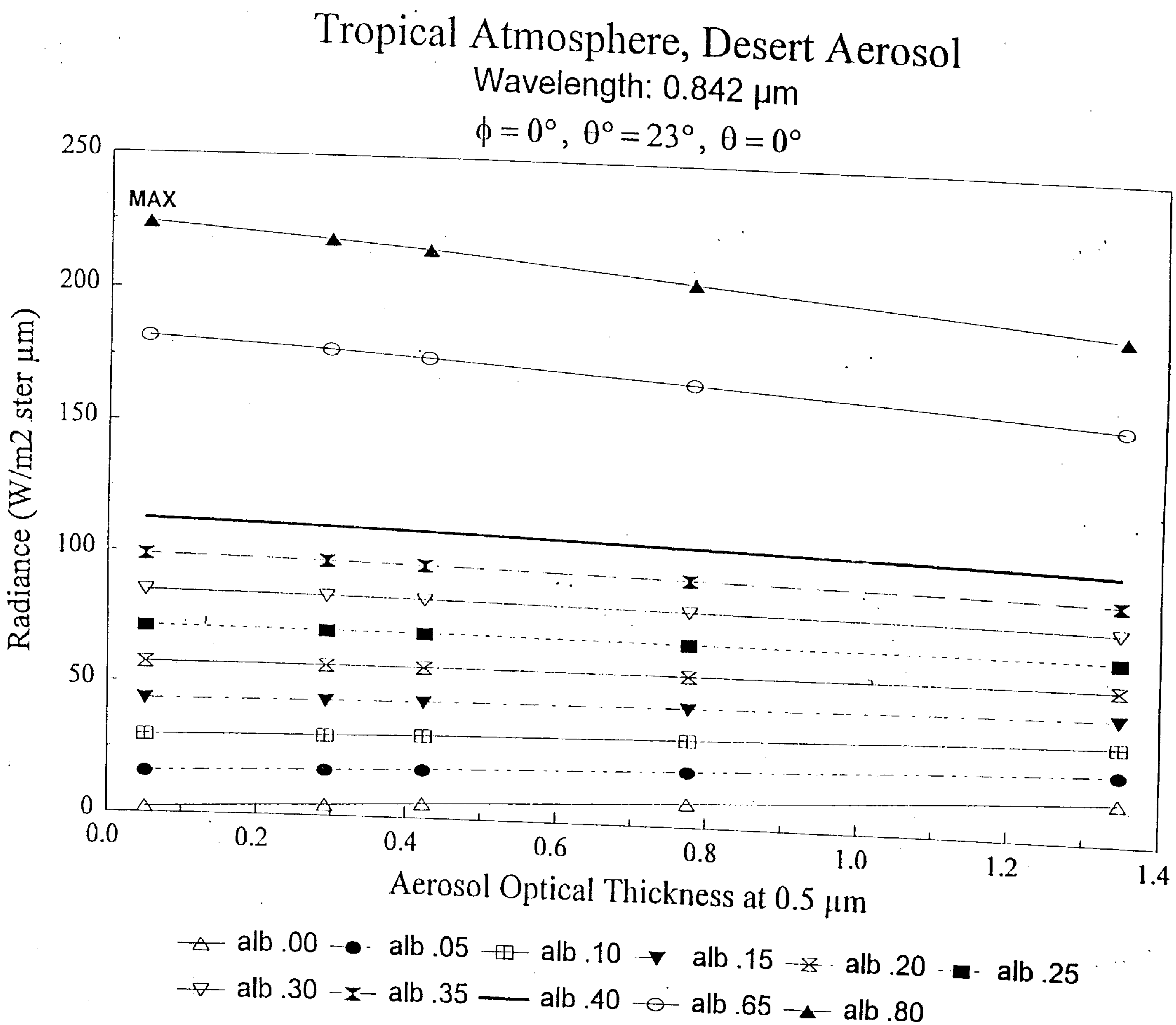

Figure 13. Upwelling radiation at the top of the atmosphere

Tropical Atmosphere, Desert Aerosol

Wavelength: 1.6 μm

$\phi = 0°,\ \theta° = 23°,\ \theta = 0°$

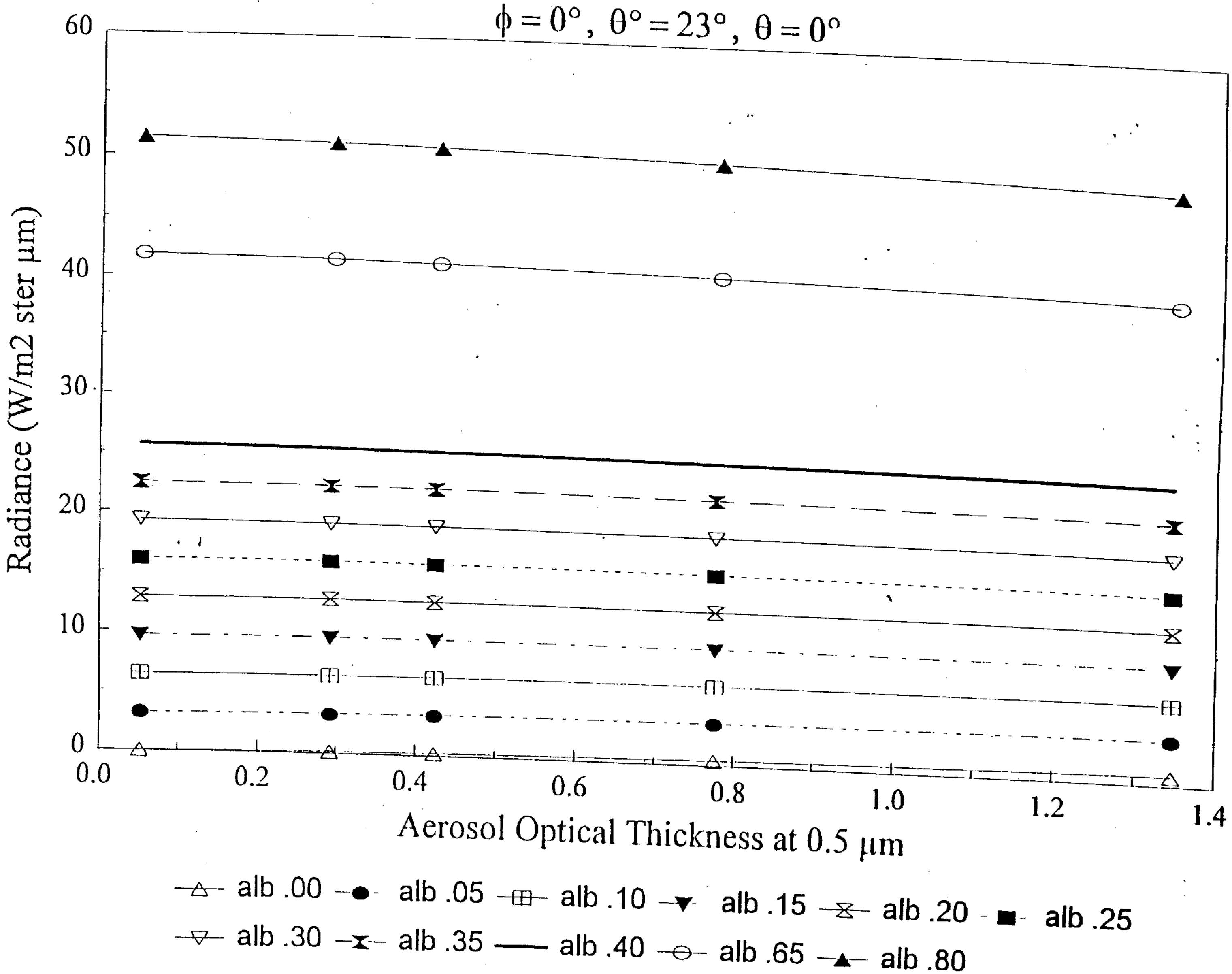

Figure 14. Upwelling radiation at the top of the atmosphere

and radiometric responses, instrumental polarization, and other issues such as spatial resolution/MTF, striping when detector arrays are used, and spectral and spatial stray light effects.

Thus, in essence, the calibration and characterization of a radiometer, when properly performed, should enable the user to: (a) identify and understand factors which affect radiometric performance; (b) develop acceptance criteria for ensuring compliance of instrument to specifications; (c) evaluate the uncertainty introduced by the changes from primary to secondary to tertiary and higher order standards of radiance and irradiance; and (d) evaluate the compatibility of the products generated with the radiometer with comparable records derived from different sources.

6.2 Pre-launch calibration

6.2.1 General

The calibration and characterization of the EOIR is rendered difficult because of the requirement that it should yield both high resolution images under low illumination conditions, and be capable of making accurate radiance measurements in precisely defined spectral intervals-- it should both be an imager and radiometer.

In the case of a broad-band sensor like the EOIR, spectral calibration would imply the precise determination of the normalized response curve for each of the channels, and ensuring out-of-band rejection to minimize cross-channel contamination. These factors provide insight into activities directed towards the inter-comparison of radiances measured in any given channel of different copies of the same instrument. Differences in spectral characteristics may lead to effects that mimic those of factors not related to the sensor. To illustrate this point, we have shown in Table 3 below the in-band extraterrestrial solar irradiance calculated using three different extraterrestrial solar irradiance spectra, and the equivalent width, w, of channel 1 of the AVHRRs on NOAA-6, -7, -8, -9, and -10 spacecraft. The differences in the in-band irradiances corresponding to different extraterrestrial solar irradiance values are comparable to those caused by the differences in the equivalent widths.

Radiometric calibration of the sensor would entail the determination of the sensor response to known input signals representative of a considerable part of, if not the entire, dynamic range of the sensor. Regression relationships are established between the sensor response and input signals(radiances), and a calibration equation is established. Linearity of response(or departure from linearity) is determined, and appropriate non-linearity correction procedures established.

Table 4. In-band solar irradiances in channel 1 of the AVHRRS on different NOAA spacecraft

Satellite	Flux[1] (w/m^2)	Flux[2]	Flux[3]	width (μm)
NOAA-6	183.8	179.0	169.6	0.109
NOAA-7	182.4	177.5	168.2	0.108
NOAA-8	188.2	183.4	174.0	0.113
NOAA-9	196.4	191.3	181.5	0.117
NOAA-10	183.8	178.8	169.4	0.108

The superscripts 1,2, and 3 indicate the extraterrestrial solar irradiance spectra of U.S. Air Force(1965), Neckel and Labs(1984), and Thekaekara(1974) respectively.

6.2.2 Visible and near-infrared regions

An integrating sphere is generally used as the calibration source in the laboratory for calibration in the visible and near-infrared regions of the spectrum; the radiance at the port which the instrument senses can be varied by switching on and off suitable combinations of stable lamps which illuminate the inside of the sphere. Some of the generic recommendations made by the National Institute of Standards and Technology regarding the calibration of satellite instruments using integrating spheres as calibration sources are:

(a) The impact of radiation back-reflected into the integrating sphere by the front optics of the sensor should be studied, and accounted for in the calibration procedure;

(b) The state of the reflecting coating of the sphere should be monitored periodically since the throughput of the sphere is very sensitive to small changes in the coating reflectance, especially when the coating is a highly reflecting material like Barium Sulfate. The integrating sphere should be frequently monitored for its radiance output against standards that are traceable to NIST; the sphere calibration should be done both immediately before and after the calibration of an instrument;

(c) A calibration history of the integrating sphere should be maintained;

(d) The deterioration of the coating when the sphere is not in use should be minimized by guarding against the circulation of unfiltered air within the sphere;

(e) Changes in the wall reflectance, and the flux of radiation back-reflected to the sphere by the instrument should be monitored, as also the emergent spectral radiance at the port; highly stable silicon cells would serve well as monitors, used in conjunction with band-pass filters as needed.

Sensors like the EOIR should be calibrated periodically while on the shelf; and as close to launch as practicable, to assess sensor degradation, if any, while on the shelf.

6.2.3 Infrared region

The thermal infrared channels are generally calibrated in the laboratory in a thermal vacuum chamber using black body sources with emissivities approaching unity. The instrument views a black body whose temperature is varied in steps over the range of Earth-scene temperatures normally encountered by the instrument while in orbit, and its output recorded. The lower reference point is provided by a black body maintained at $\approx 77^0$ K to simulate space. A linear or a quadratic relationship is established between the radiance of the Earth scene black body, and the instrument output, and used as the calibration equation. Particular attention should be paid to account for the sensor nonlinearities, if any. Presently in NOAA/NESDIS, a user friendly procedure to correct for sensor non-linearties which is based on the "non-zero radiance of space" concept, and which uses the intercept and slope values derived fron the on board, linear calibration of the thermal infrared channels of the AVHRR is used to correct for the non-linear response of the Mercury-Cadmium-Telluride detectors.

It has been noticed with the AVHRR that the instrument response when it views the space simulator in the pre-launch laboratory calibration can be different from the instrument response when it views space in orbit. The "non-zero radiance from space" concept has been invoked to correct for this discrepancy.

6.3 On board calibration

6.3.1 Infrared channels

We shall first discuss the on board calibration of the thermal infrared channels since most of the satellite instruments operating in the infrared region of the spectrum have on board calibration devices. The device normally consists of an on board black body operating at a known temperature which is measured by a bank of platinum resistance thermometers whose calibration can be traced to NIST. The radiance from this black body serves as the upper calibration point; the lower calibration point is provided by the space look. Thus, a two-point linear calibration is established as often as desired in orbit. Brightness temperatures derived from this two point calibration are corrected for sensor nonlinearities. It has been the practice with the AVHRR to transfer the laboratory calibration of the AVHRR based on viewing the Earth-scene black body to the on board black body, commonly referred to as the Internal Calibration Target. It should be noted that thermal gradients across the Internal Calibration Target may adversely affect the on board calibration. The option of using more than one on board Internal Calibration Target should be explored.

6.3.2 Visible and near-infrared channels

Based on our experience with the AVHRR, we should expect that the visible and near-infrared channels of the EOIR will degrade in orbit(see Fig.15). Thus, to ensure the integrity and long-term continuity of the products generated using the measured radiances in the spectral region from ≈ 0.5 - $2\mu m$, it is essential to provide for the on board calibration of the EOIR channels in this region of the spectrum. However, the on board calibration in this spectral region is rather difficult because of the general lack of illumination sources for on board use which will remain stable in their spectral and radiant output for periods comparable to the operational life of the satellite instrument. Two possible schemes are:

(a) Calibration using a standard lamp, or a series of lamps on board, in conjunction with an integrating sphere, or a diffuser. The lamps will draw power from the spacecraft, and add to the volume and weight of the instrument. Light emitting diode bundles have also been used as on board light sources for calibration(e.g., MISR).

(b) Calibration using the sun or the moon as the calibration source, in conjunction with a diffuser plate. The use of a deployable diffuser is preferred. The stability of the diffuser in orbit must be monitored. This can be achieved with a separate on board detector which views the sun directly, and on reflection by the diffuser. The ratio of the two signals is a measure of how stable the diffuser is. The wavelength dependency of the bidirectional reflectance of the diffuser should be known.

The moon offers itself as an attractive calibration source since its reflectance remains stable to one part in 10^9(?) per year. The requirement for viewing the moon at similar illumination/observation angles, in order to avoid making corrections for changes in the bidirectional reflectance, may necessitate maneuvering the entire spacecraft which may pose considerable risk to the mission. The advantages of using the moon as a calibrator are: (a) its ability to serve as a stand-alone in-flight calibrator; and (b) its utility as an independent validation of the precision of a calibrated time series.

6.3.3 Vicarious calibration of the visible and near-infrared channels

Vicarious calibration of the visible and near-infrared channels of the EOIR should be an integral part of the post-launch characterization of the EOIR. It will serve (a) to monitor the performance of the on board calibrator within predetermined broad bounds; and (b) as a replacement for the on board calibrator in the event of the latter's failure in orbit. Vicarious calibration is generally performed using:

(a) Statistical methods: This technique is based on monitoring the upwelling radiance over radiometrically stable desert targets(e.g., Libyan desert) over long periods of time to determine relative degradation. The advantages are: the use of bright desert targets minimizes atmospheric effects; and the use of a large body of data results in the reduction of noise, and provides insight into long-term trends. The disadvantages are: the technique yields only relative degradation rates, and assumes a single mathematical description for instrument performance for the entire time series;

(b) Aircraft underflight method: The method is based on simultaneous aircraft and satellite observations of bright targets along congruent paths. The advantages are: the use of a bright surface minimizes atmospheric effects; and the technique requires fewer assumptions and less modelling than any other method, and yields absolute calibration accuracies of the order of 5%. The disadvantages are the cost, and the stringent demands on pointing accuracies;

(c) Simulation methods: These are based on radiative transfer calculations to predict upwelling radiance at the satellite. The radiance is then regressed against the instrument response to obtain a calibration. Both bright desert surfaces and dark ocean surfaces have been used in the model simulations. With a bright desert surface, the calibration accuracy is influenced by how faithfully the reflection characteristics of the surface have been represented in the model simulations; and with dark ocean surfaces, the upwelling radiances are very low, and thus inaccuracies in modelling the surface and atmosphere will severely affect the results; also requires large amounts of ancillary data.

To illustrate the absolute need for on board calibration, and the usefulness of vicarious calibration, we have shown in Fig.14 the time series of the surface albedo(in per cent) of the southeastern part the Libyan desert(20-21^0 N; 27-29^{0}E) in channels 1 and 2 of the AVHRRs on the NOAA-7, -9, and -11 spacecraft covering period from 1981 to 1991. The albedo in either channel is given by $100(\pi I)/F\cos\theta_0$, where I and F are respectively the in band radiance and extraterrestrial solar irradiance in the channel of interest, and θ_0 is the solar zenith angle. It is apparent that the use of pre-launch calibrations, which do not correct for the in-orbit degradation of the two channels, will result in spurious trends, and in discontinuities in the time series during the transition from one satellite to the next. On the other hand, use of the post-launch vicarious calibrations which account for the in-orbit sensor degradation, removes the spurious trends, and the restores the continuity of the time series. We should expect that a combination of on board and vicarious calibration procedures would yield high quality radiance measurements from the EOIR.

We have summarized in Table 5 the pre- and post-launch calibration features, and related information associated with various satellite instruments we reviewed. Some of the factors to which particular attention should be paid in the design of an on board calibrator are: (a) the bidirectional reflection distribution function(BRDF), and wavelength dependence of reflection by materials like Spectrolon, pressed halon, sintered halon, and alluminium used in the diffuser/mirror assemblies when the sun or moon is used as the external calibration target; (b) the stability of the diffuser in time; (c) impact of gas leakage on the radiometric stability of mercury-halogen lamps used as on board calibration sources; (d) the quantum efficiency of photodiodes used as on board calibration sources; (e) the absorptivity of on board blackbody sources used as internal calibration targets; and (f) thermal gradients across the internal calibration targets.

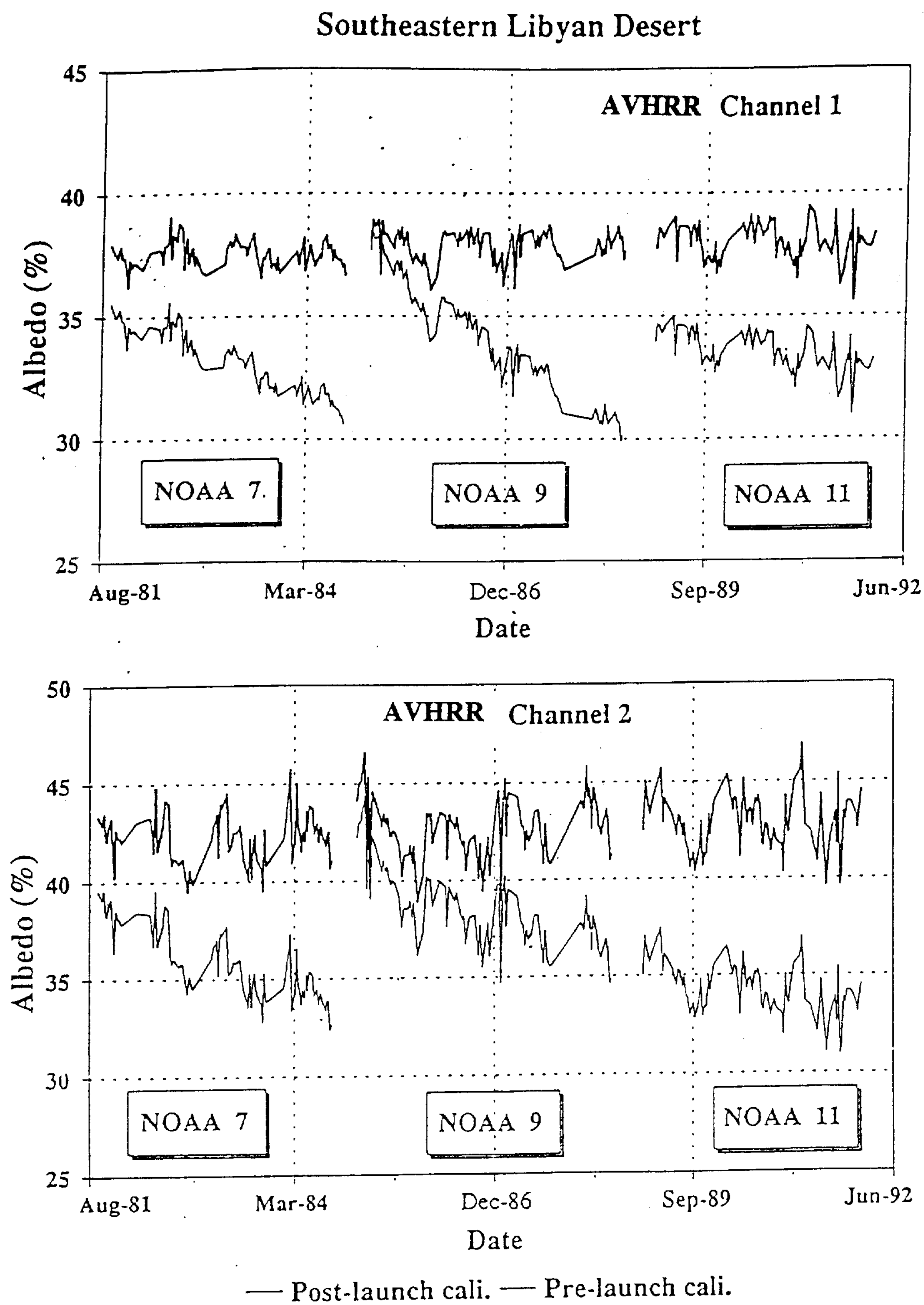

Figure 15. Isotropic albedo in channel 1(top) and channel 2(bottom) of the southeastern Libyan desert

Table 5. Calibration and related features of selected satellite radiometers					
Instruments	AVHRR	MODIS	MISR	SeaWiFS	(A)ATSR
I. Pre-launch Calibration Sources					
Integration Sphere	√	√	√	√	
Blackbody Source	√	√			√
Calibrated Lamps			√	√	
External source				Direct Sun	
I I. Post-launch Onboard Calibration					
Lamps sources		√	Diodes		
Blackbodies	√	√			√
III. Post-launch External Calibration Sources					
Solar Diffuser		?	√*	√*	
Lunar View		?		√*	
Earth Scenes	√	√	√		√*
Deep Space	√	√			
Notes:			*Diffuser monitored by diodes	*Low gains solar/lunar modes	*1.6 μm uses White Sands
IV. Detectors and Dispersive Elements					
Dispersive Elements	Interference	Dichroic	Detector-bonded Filters	Dichroic	Multilayer Filter
Detectors	Si, In Sb, HgCdTe	Si, In Sb, HgCdTe, InGaAs	CCD's, LED's	Silicon	In Sb, HgCdTe

7. Preliminary Recommendations

7.1 Spectral intervals

The preliminary choice of the spectral intervals for the Electro-Optical Imager and Radiometer is governed by our experiences with the different versions of the Advanced Very High Resolution Radiometer(AVHRR), and by the history of the applications and use of the long term records of geophysical products that have been generated using the AVHRR. In addition, information available in the public domain indicates that there is considerable overlap with the spectral intervals chosen for the Operational Multispectral Imaging Suite and the AVHRR(and VIRSR). Our choice has also been influenced by the fact that the AVHRR has served as a model for various research and operational satellite instruments(e.g., MODIS). We therefore suggest that:

> The basic EOIR be designed to make measurements of the upwelling radiance at the top of the atmosphere in spectral intervals around 0.55, 0.62, 0.87, 1.6, 3.7, 8.6, 10.8, and 12μm; in addition, a broad band channel, encompassing the visible and near-infrared, from $\approx$0.4 to 1μm be included for low light level measurement.

The above choice of spectral intervals essentially combines the attributes of the NOAA's Visible, Infrared Scanning Radiometer(VIRSR) and DoD's Operational Multispectral Imaging Suite(OMIS).

An eminently desirable option is to incorporate into the EOIR ocean colour sensing capabilities with the inclusion of narrow band-pass channels in the visible and near-infrared; the starting point would be the SeaWiFS channels centered on $\approx$o.41, 0.44, 0.49, 0.51, 0.55, 0.67, 0.76, and 0.86μm. However, inclusion of the ocean color sensing channels may impact the optical, mechanical, and electrical subsystems, and cost of the EOIR. It is our intention to examine this impact if the EOIR internal concept study is continued in FY1996.

7.2 Post-launch characerization

In regard to the post-launch characterization of the EOIR, we recommend that:

> The EOIR should have on board calibration capability. This can be achieved with on board calibrators using the sun as a calibration source, in conjunction with a diffuser plate. In addition, the possibility of having secondary on board calibrators using lamps/photodiodes should be examined. The objective should be to attain on board calibration capabilities which would improve upon what can be presently achieved with vicarious techniques. As mentioned earlier, it

is conservatively estimated that present vicarious calibration techniques are accurate to 5%.

This would entail a detailed analysis of the performance of systems that have been proposed for instruments such as the MODIS, MISR, SeaWiFS, etc. Studies along these lines have already been initiated as part of the FY1995 Internal Concept Study, and will be the basis for the establishment of design criteria for the bread board design of an on board calibrator for the EOIR if this study is continued in FY1996.

7.3 Sensor specification

In view of the algorithm-specific effects that will invariably influence the translation of the product requirements into sensor specifications(Figure 1), we further recommend that:

The merits of drawing the specifications for the EOIR in terms of the radiances which are the measured physical quantities rather than in terms of the Environmental Data Records or products be earnestly investigated, and EOIR specifications be written in terms of radiances, and related sensor- or instrument-based characterisitics.

The reader may get the impression that we have so far dealt with generalities, and not specifics such as, for example, the spectral characterization(band width, shape of the normalized response curve, etc) of the various channels for the EOIR, signal to noise ratios, noise equivalent temperatures, instrument polarization, detailed design of the on board calibration device, etc. These specifics will be attended to when the revised version of the Integrated Operational Requirements Document(IORD) becomes available with the product requirements specified in detail so that the high level design of the EOIR, including the on board calibrator, would meet the same(product requirements) in an optimum manner.

8. Planned activities for FY1996

a. Translation of product requirements to sensor specifications

Starting with a representative list of <u>finalized</u> Environmental Data Records(EDRs)or products in the <u>Integrated Operational Requirements Document(IORD I)</u> that can most probably be derived from the radiances measured in the visible and infrared regions of the spectrum, the product requirements will be translated into sensor requirements via established operational and research algorithms; particular attention will be paid to identify algorithm-specific issues, and quantify their impact on sensor specifications to the extent practicable. User- and product-scientist input will be sought as needed to facilitate this activity. An attempt will be made to identify the major driver(s) of sensor performance requirements.

b. Sensor concept and design

Using the results of (a) above, the high level sensor concept will be extended to more practical levels, taking into consideration the final Environmental Data Record or product requirements in IORD 1. This would include specification of: (i) spectral intervals (e.g., centroid wavelength, band width, slope of the normalized response function, etc.); and (ii) other sensor attributes such as signal to noise ratios, noise equivalent temperatures, polarization sensitivity, sensor linearity and departures therefrom. Particular attention will be paid to the performance of the Mercury-Cadmium-Telluride detectors generally used in the thermal infrared regions either in the photo-conductive or photovoltaic mode.

c. Bread-board design of on board calibrator

The review of the available techniques for on board calibration for the entire spectral region to be covered by the EOIR will be completed, and the criteria for the design for a bread-board model of an on board calibrator for the visible and near-infrared channels will be established. The rationale for the choice of the proposed technique will be explained. A detailed discussion of the relative merits and limitations of different techniques which are currently in use, or which have been proposed for various environmental sensors will be provided. The feasibility of using multiple on board black-body calibration targets for the thermal infrared regions will be investigated so that the implementation of corrections for sensor non-linearities, if warranted, will be facilitated.

d. Vicarious calibration

The post-launch performance of the integrated sensor has to be assessed periodically even when it is equipped with an on-board calibrator, to ensure that the on board calibrator is performing satisfactorily, and is indeed meeting the long-term precision/stability criteria. Procedures for the vicarious calibration of the EOIR will be developed to ensure that the instrument is performing within previously determined **broad** bounds.

e. End-to-end model simulation of sensor performance

Representing sensor-specific issues such as noise, sensor deterioration, calibration uncertainties, and technology imposed constraints on sensor performance as perturbations in the measured upwelling radiances, the impact of the same on the retrieved products or EDRs will be studied through radiative transfer model simulations under representative conditions yet to be determined.

This will have a bearing on our ability to define the realizability of a product (see also Section 2.2b).

f. Product Dossiers

After the finalization of the IORD, using the desired "threshold" and "objective" values for the accuracy, and short- and long-term precision, product dossiers for selected, EOIR-derived key and non-key parameters (e.g., vegetation index, atmospheric aerosols, surface albedo, etc.,) will be generated to illustrate the translation of product requirements to sensor requirements. This activity will be restricted to those parameters the requirements for which have been completely specified.

g. Value-added Environmental Data Record (VAEDR)

We define a Value-added Environmental Record (VAEDR) as a geophysical product or Environmental Data Record which has been assembled from multi-sensor, multi-temporal measurements. It is expected that VAEDRs will enhance the utilization of the products generated by NPOESS by the user community as they will have greater spatial and temporal coverage, and greater global representativeness. Some of the issues to be addressed in the fusion of measurements/products from different sources are: (i) inter-satellite and cross-satellite sensor calibration; (ii) reconciliation of differences in spatial and temporal resolutions; (iii) differences in navigational requirements of different sensors; (iv) discontinuities in time series; (v) algorithm-specific features of the products; and (vi) the logistics of fusion of data with different formats. Methodology to resolve some of these issues will be illustrated with the sea surface temperature product, utilizing the presently available information on the same as it is derived from the AVHRR, and the ATSR. The impact of the aerosol product on the attainable SST accuracies will also be included in this discussion.

Appendix A: Basic spectral features of selected satellite radiometers

We have listed in this appendix the very basic spectral features--essentially the spectral intervals, or central wavelengths of spectral intervals-- of selected satellite radiometers which have either been flown, or have been proposed for future space missions. The information given here is intended to expand upon the information given in Table 2, and to bring out the basic philosophy of utilizing the available information on atmospheric and surface spectral signatures in the design of satellite radiometers. When spectral intervals are given, no attempt has been made to associate the short- and long-wavelength limits with any response values(e.g., 1%, 10%, or 50%).

1. Advanced Very High Resolution Radiometer(AVHRR)

   Version 1: ≈0.58-0.68; 0.72-1.10; 3.55-3.95; 10.5-11.5μm

   Version 2: ≈0.58-0.68; 0.72-1.10; 3.55-3.95; 10.3-11.3; 11.5-12.5μm

   Version 3: ≈0.58-0.68; 0.725-1.0; 1.58-1.64; 3.55-3.93; 10.3-11.3; 11.5-12.5μm

2. Visible Infrared Scanning Radiometer(VIRSR)
   (Source: Original specification document)

   ≈0.615; 0.870; 1.61; 3.72; 8.55; 10.8; 12.0μm

3. Moderate-Resolution Imaging Spectroradiometer(MODIS)

   21 spectral bands within 0.4-3.0μm; 15 within 3-14.5μm

4. Sea-viewing Wide Field-of-view Sensor(SeaWiFS)

   0.402-0.422; 0.433-0.453; 0.480-0.500; 0.500-0.520; 0.545-0.565; 0.660-0.680; 0.745-0.785; 0.845-0.885μm

5. Multi-angle Imagind Spectrometer(MISR)

   ≈0.443; 0.555; 0.670; 0.865μm

6. Along Track Scanning Radiometer(ATSR)

   ≈1.6; 3.7; 11; 12μm

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